# Bimodal SLD Ice Accretion on a NACA 0012 Airfoil Model

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# Outline

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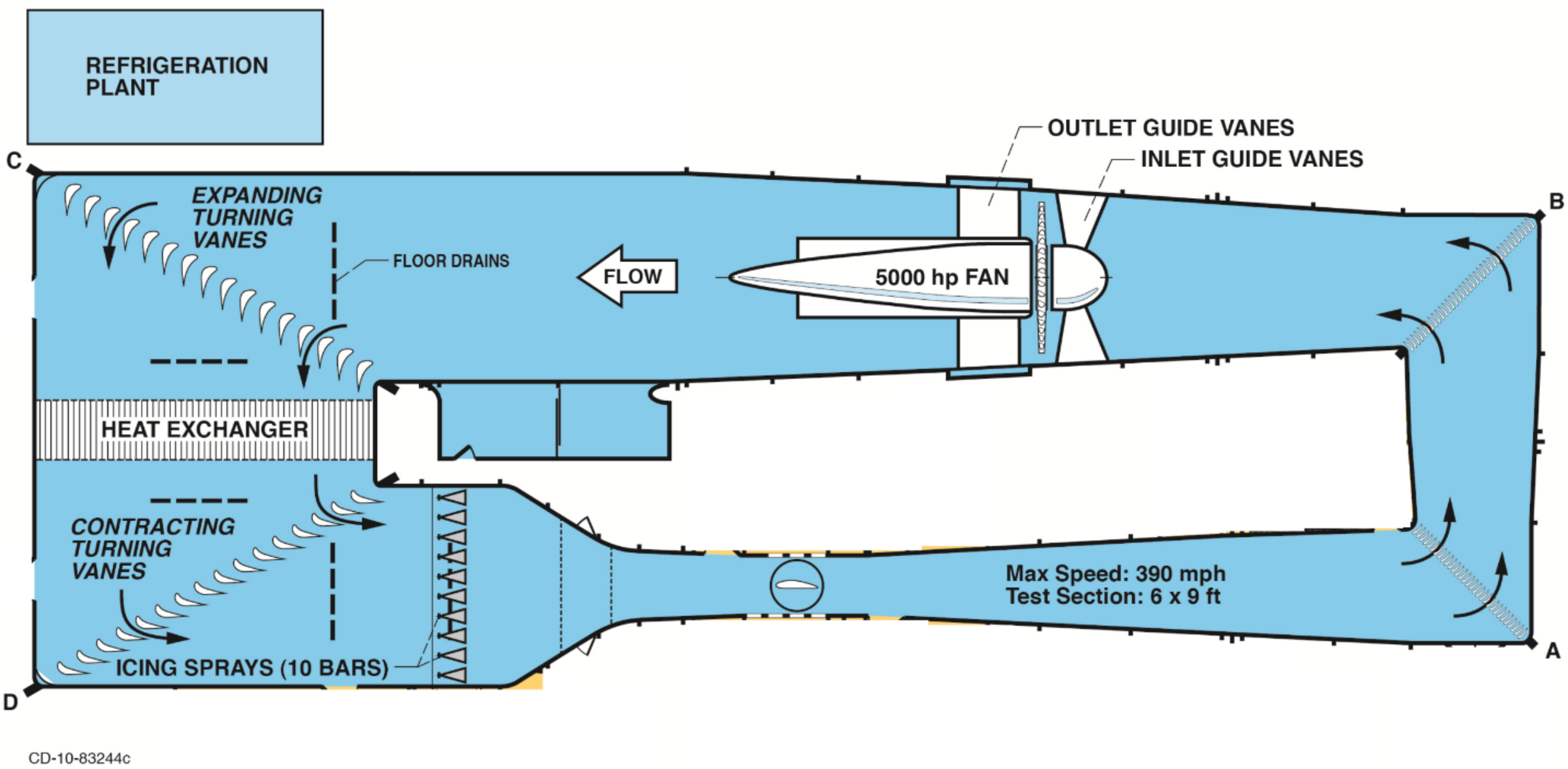
# Objectives

1. Document the Ice Shapes Produced using the IRT Bimodal Spray Conditions
2. Compare with Ice Shapes Produced using the Single Nozzle Array (Monomodal) for Equivalent Cloud Conditions
   - Use previously produced ice shapes as reference conditions

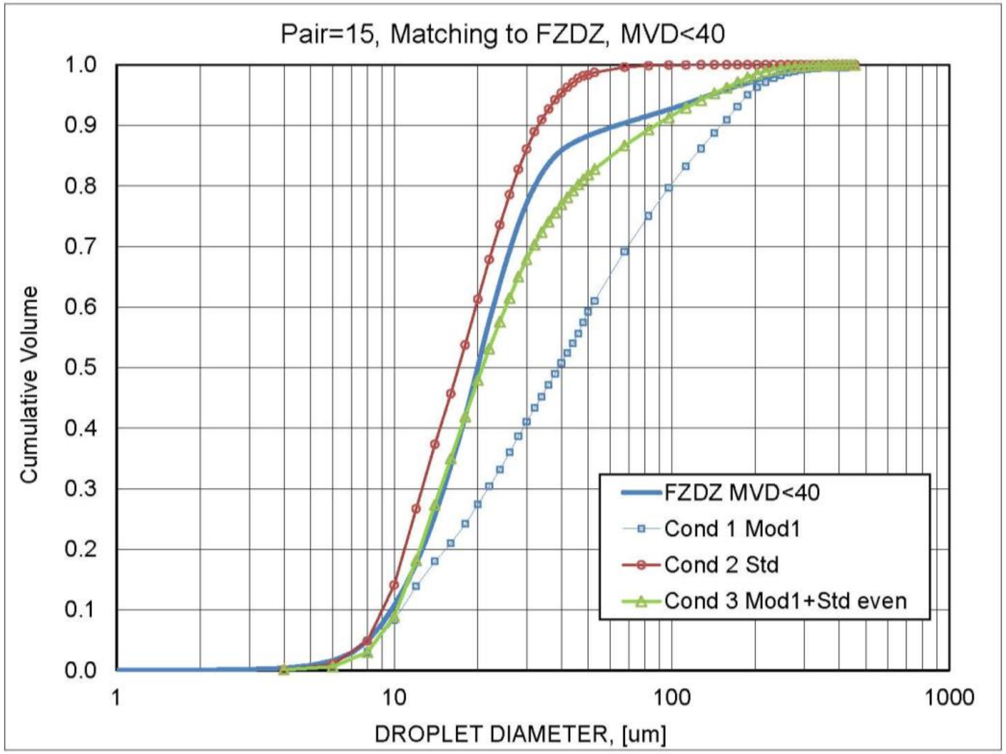
# Approach

1. Evaluate the IRT Bimodal Spray Ice Shapes
   - At 130, 150, 200 & 250 knots
   - At $\alpha = 0^{\circ}, 4^{\circ}$
2. Compare with Monomodal Spray Ice Shapes at
   - 2 Ice Shape Repeatability Conditions
   - 2 Ice Shape Condition from Scaling Work

# NASA Icing Research Tunnel



# 2016 IRT Bimodal Spray




Pair = 15 psig

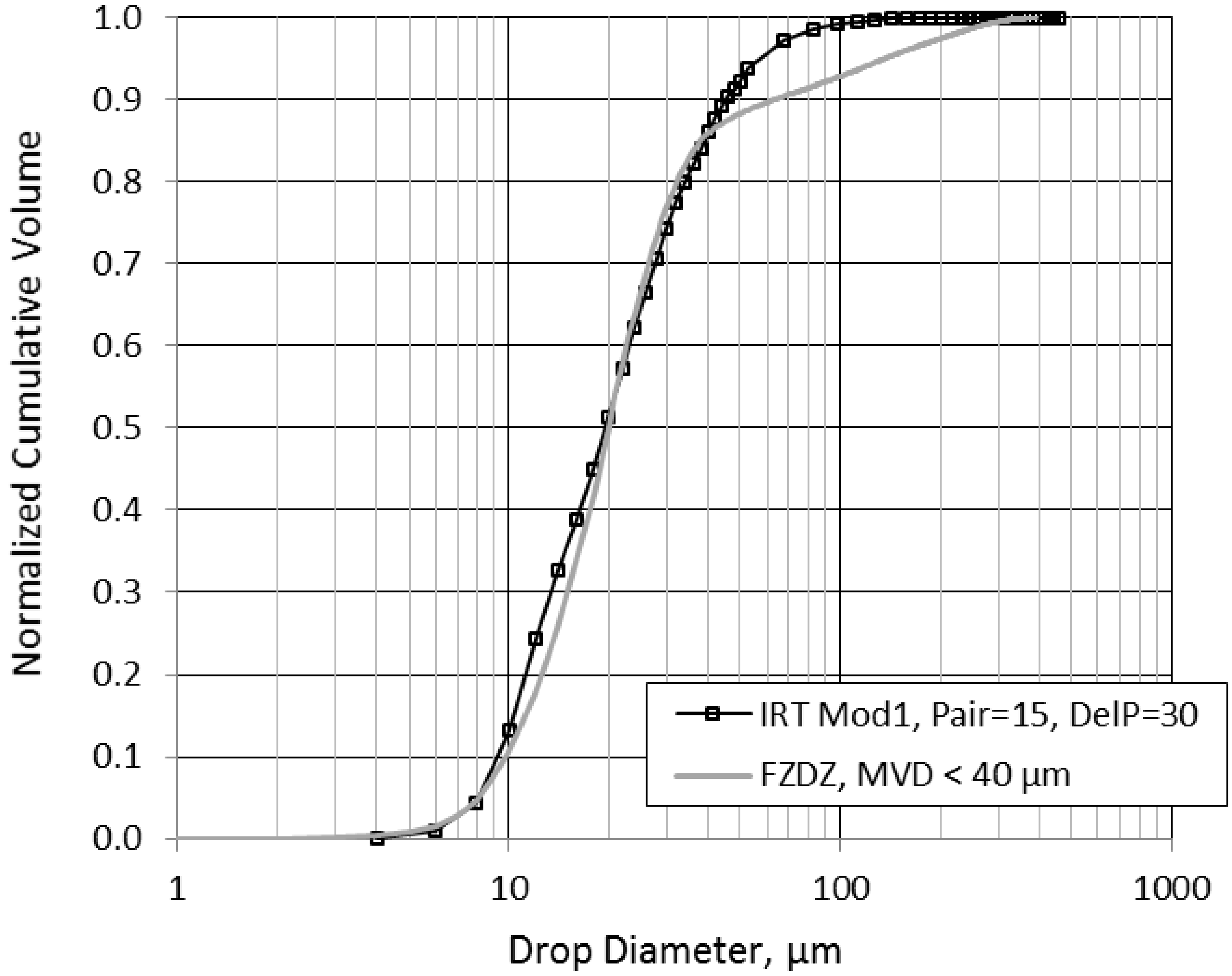
- Man1 (Mod1) deltaP = 80 psid
  - MVD = 39.2 um
  - minLWC (@250 kts)* = 0.67 g/m$^3$
- Man2 (Std) deltaP = 7 psid
  - MVD = 17.1 um
  - minLWC (@250 kts)*= 0.78 g/m$^3$
- Combined:
  - MVD = 20.8 um
  - minLWC (@250 kts)* = 1.45 g/m$^3$

- How good of a match is it to FZDZ, MVD<40?
  - The normalized cumulative LWC in each of the measured bins was within 10% of what the normalized cumulative LWC is for FZDZ, MVD<40 (for each corresponding bin)

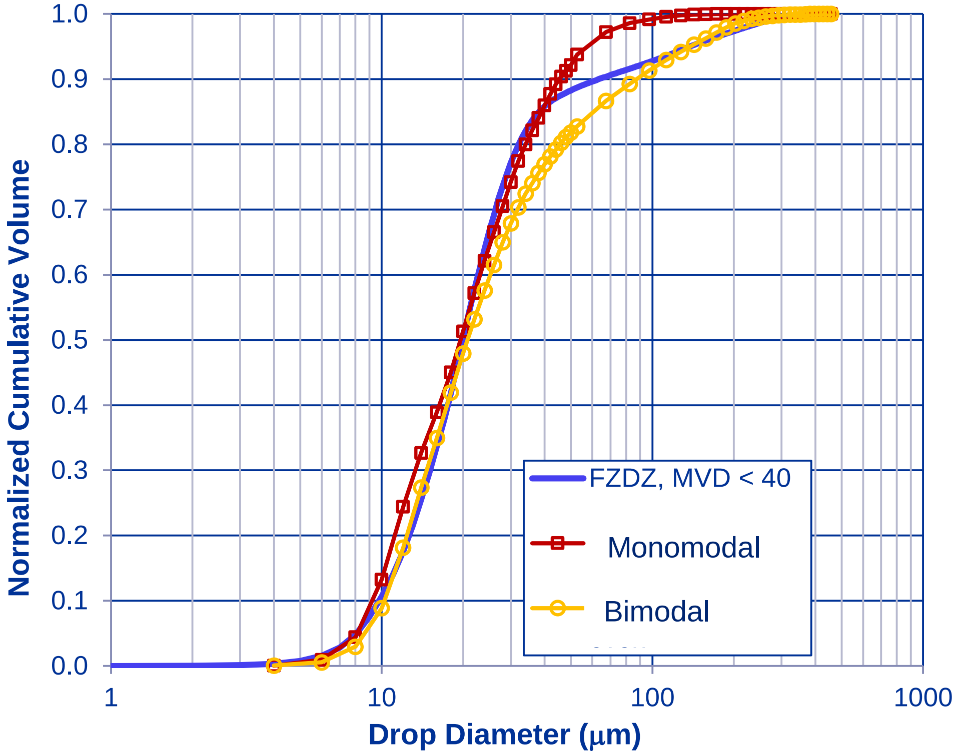
*LWC values based on IRT LWC calibration curves

# Selected IRT Mod1 Spray Condition

## *Monomodal Distribution*



# 2016 IRT Bimodal & Monomodal Distributions




- FZDZ, MVD<40
  - FAA App O distribution
  - MVD=20 µm
  - LWC between 0.29 and 0.44 g/m$^3$
- Bimodal
  - Mod1 + Std nozzles
  - Pair = 15 psig
  - Mod1 DeltaP = 80 psid
  - Standard DeltaP = 7 psid
  - Combined MVD = 20.8 µm
  - Combined minLWC (@250 kts) = 1.45 g/m$^3$
- Monomodal
  - Mod1 nozzles
  - Pair=15 psig
  - DelP=30 psid
  - MVD=19.3 µm
  - minLWC (@250 kts) = 0.37 g/m$^3$

- Both IRT distributions were measured by spraying only even-numbered spray bars, as is typical for drop-sizing calibrations in Appendix C conditions in order to avoid coincidence error
- LWC values are based on IRT calibration curves

# Test Model


21-in chord NACA 0012 model, full span

# Test Procedures

- The tunnel temperature and velocity conditions were set.
- The spray bar air and water pressures were set.
- The tunnel was run at the set temperature and velocity conditions and the thermocouples on the model were monitored.
- When the model temperature matched the tunnel static air temperature, the model was considered to be sufficiently cold to initiate the spray.
- The spray was initiated and lasted for the prescribed time for the icing condition of that run.
- After the spray was stopped and the tunnel velocity was reduced to idle conditions, personnel entered the test section and performed the following tasks.
- Photographs of the ice on the model were taken from several pre-set locations around the model.
- A laser scanner system was used to obtain geometric data of the ice shape using the method described by Lee, et al.*
- Once the ice shapes were scanned, a 12 inch spanwise section of the ice shape was removed from the surface into a collection tray and weighed in order to obtain the accumulated mass.
- Following the removal of the mass, the model surface was cleaned of all remaining ice and prepared for the next test run.

*Lee, S., Broeren, A.P., Kreeger, R.E., Potapczuk, M., and Utt, L., "Implementation and Validation of 3-D Ice Accretion Measurement Methodology," AIAA 6th Atmospheric and Space Environments Conference, Atlanta, GA, June 16-20, 2014, AIAA Paper 2014-2613.

# Test Matrix

## 5 proposed reference conditions

| Test Conditions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Case | Reference Condition | α | V (kts) | MVD (mm) | LWC ($g/m^3$) | $T_t$ (°C) | $T_s$ (°C) | Time (min) | $n_0$ |
| Ice Shape Repeatability Run 3 | 1 | 4 | 200 | 20 | 0.55 | -5.6 | -10.8 | 7 | 0.52 |
| Ice Shape Repeatability Run 23 | 2 | 4 | 130 | 22 | 1 | -5.6 | -7.8 | 6 | 0.34 |
| 5-15-06/Run 14 | 3 | 0 | 150 | 30 | 1.34 | -12.5 | -15.5 | 5.5 | 0.49 |
| 5-15-06/Run 15 | 4 | 0 | 100 | 30 | 1.75 | -13.5 | -14.8 | 6.7 | 0.5 |
| 3-28-05/Run 6 | 5 | 0 | 250 | 26.8 | 0.56 | -5.2 | -13.4 | 8.5 | 0.46 |

Note: For scaling, two selected spray clouds are considered

# Test Matrix

## Monomodal and bimodal test conditions based upon scaling of reference conditions.

| Run # | Reference Condition | α | V (kts) | MVD (mm) | LWC ($g/m^3$) | $T_t$ (°C) | $T_s$ (°C) | Time (min) | $n_0$ | *Mod-1* *$p_{air}$*, psig | *Mod-1* *Dp*, psid | *Std* *$p_{air}$*, psig | *Std* *Dp*, psid |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AE2716 | 5.b | 0 | 250 | 19.3 | 0.37 | -2.3 | -10.5 | 14 | 0.46 | 15 | 30 | | |
| AE2717 | 2.b | 4 | 130 | 19.3 | 0.55 | -2.8 | -5 | 11.5 | 0.34 | 15 | 30 | | |
| AE2718 | 1.b | 4 | 200 | 19.3 | 0.42 | -3.9 | -9.2 | 9.3 | 0.52 | 15 | 30 | | |
| AE2719 | 2.a | 4 | 130 | 20.8 | 2.15 | -9.9 | -12.1 | 2.9 | 0.34 | 15 | 80 | 15 | 7 |
| AE2720 | 5.a | 0 | 250 | 20.8 | 1.45 | -11.9 | -20.2 | 3.5 | 0.46 | 15 | 80 | 15 | 7 |
| AE2721 | 1.a | 4 | 200 | 20.8 | 1.64 | -15.2 | -20.5 | 2.3 | 0.52 | 15 | 80 | 15 | 7 |
| AE2738 | 5.b | 0 | 250 | 19.3 | 0.37 | -2.3 | -10.5 | 14 | 0.46 | 15 | 30 | | |
| AE2739 | 2.b | 4 | 130 | 19.3 | 0.55 | -2.8 | -5 | 11.5 | 0.34 | 15 | 30 | | |
| AE2740 | 3.b | 0 | 150 | 19.3 | 0.5 | -4.2 | -7.2 | 17 | 0.49 | 15 | 30 | | |
| AE2741 | 2.a | 4 | 130 | 20.8 | 2.15 | -9.9 | -12.1 | 2.9 | 0.34 | 15 | 80 | 15 | 7 |
| AE2742 | 3.a | 0 | 150 | 20.8 | 1.96 | -14.9 | -17.9 | 4.2 | 0.49 | 15 | 80 | 15 | 7 |

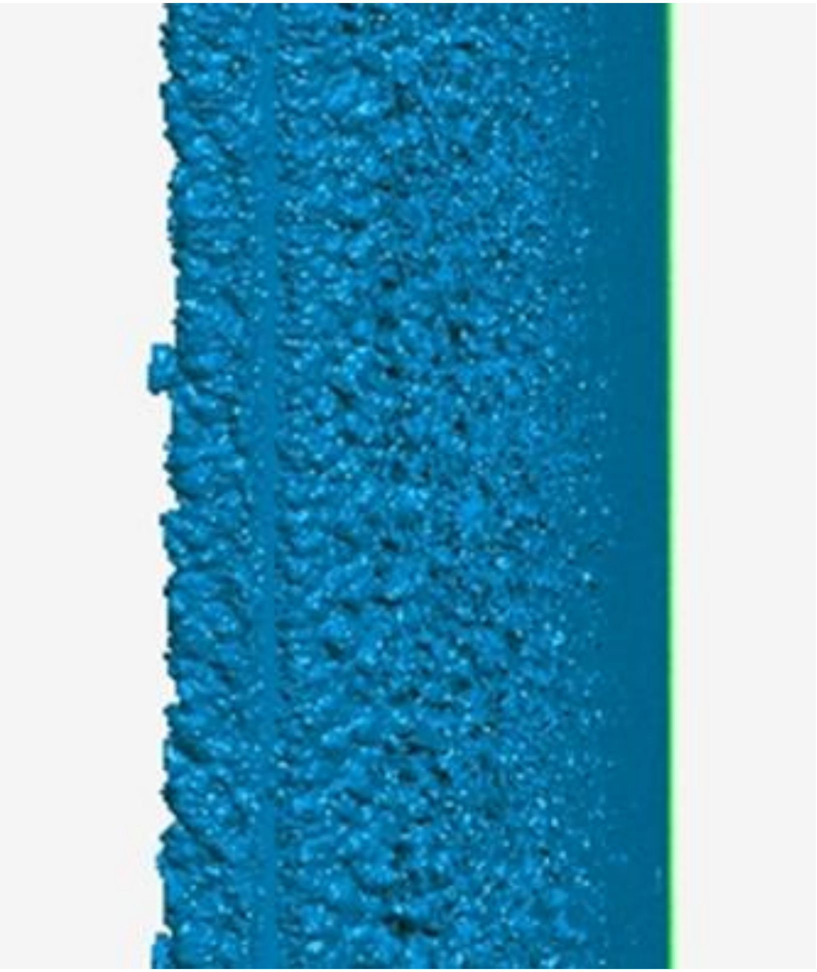
Note: a - Bimodal spray; b - Monomodal spray

# Olsen Method for Scaling LWC

1. $c_s = c_r$
2. $V_s = V_r$
3. $MVD_s = MVD_r$
4. Choose a $LWC_s$
5. Calculate the scale temperature $T_{st,s}$ from $n_{0,s} = n_{0,r}$
6. Calculate the scale total temperature, $T_{tot,s}$. If $T_{tot,s}$ is greater than -2˚C, repeat steps 4, 5, and 6 with a larger $LWC_s$
7. Calculate the scale accretion time from $A_{c,s} = A_{c,r}$, which leads to $t_s = (LWC_r \times t_r)/LWC_s$

# Sample Photograph and Scan

*Test Run #AE2741*



# Test Results

## *Quantitative Data*

Mass and volume measurements for the ice shapes resulting from the scaled monomodal and bimodal distribution icing conditions from this test program.

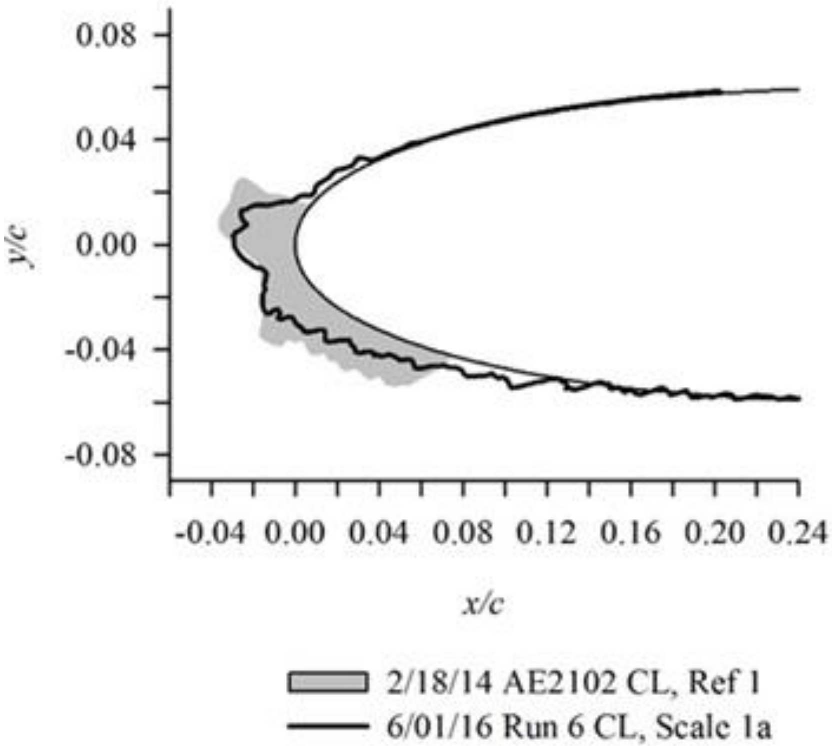
**Test Results**

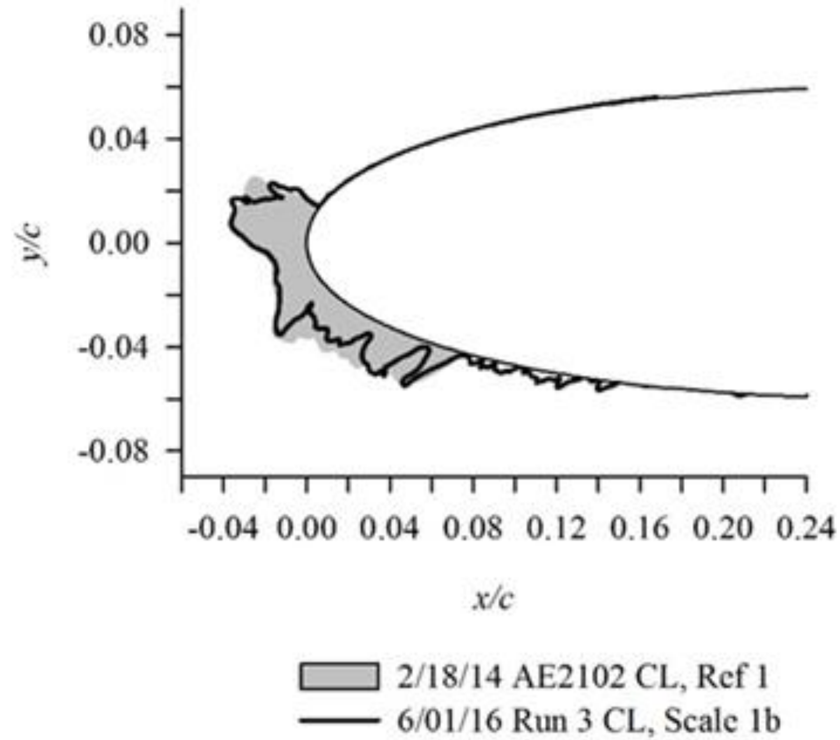
| Reference Condition | Mass bimodal (g) | Mass monomodal (g) | $\Delta m_i$ (g) | $\Delta m_i$ % | Volume bimodal $in^3$ | Volume monomodal $in^3$ | $\Delta$Vol. $in^3$ | $\Delta$Vol. % | $\rho_{eff,b}$ $g/in^3$ | $\rho_{eff,m}$ $g/in^3$ | $\Delta\rho_{eff}$ % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 163.1 | 131.2 | 31.9 | 24% | 13.67 | 12.39 | 1.28 | 10.3% | 11.9 | 10.6 | 12.7% |
| 2 | 151.9 | 137.9 | 14 | 10% | 14.3 | 11.28 | 3.02 | 26.8% | 10.6 | 12.2 | -13.1% |
| 3 | 207.1 | 188 | 19.1 | 10% | 18.46 | 15.49 | 2.97 | 19.2% | 11.2 | 12.1 | -7.6% |
| 5 | 228.5 | 157.8 | 70.7 | 45% | 19.52 | 13.56 | 5.96 | 44.0% | 11.7 | 11.6 | 0.6% |

Note: Density of ice at 0˚C is 0.9167 $g/cm^3$ = 15.02 $g/in^3$

# Ice Shape Comparisons to Reference Shapes

## Reference Condition 1, V= 200 knots




$MVD_1$ = 20 $\mu$m, $LWC_1$ = 0.55 g/m$^3$, $t_1$ = 7 min
$MVD_{1a}$ = 20.8 $\mu$m, $LWC_{1a}$ = 1.64 g/m$^3$, $t_{1a}$ = 2.3 min

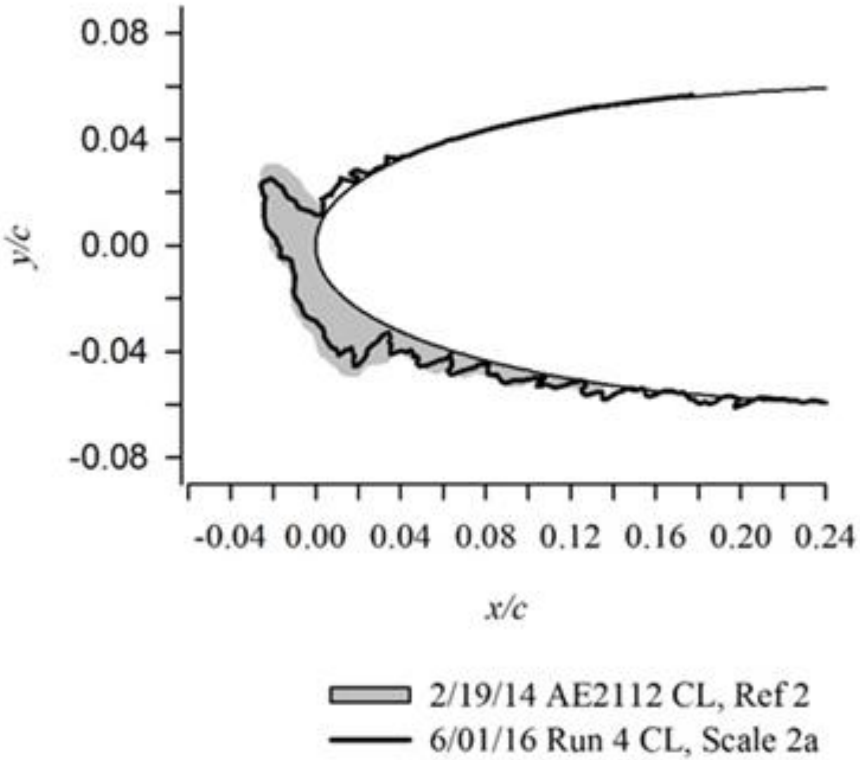
# Bimodal Distribution (a)

$MVD_1$ = 20 $\mu$m, $LWC_1$ = 0.55 g/m$^3$, $t_1$ = 7 min
$MVD_{1b}$ = 19.3 $\mu$m, $LWC_{1b}$ = 0.42 g/m$^3$, $t_{1b}$ = 9.3 min

# Monomodal Distribution (b)

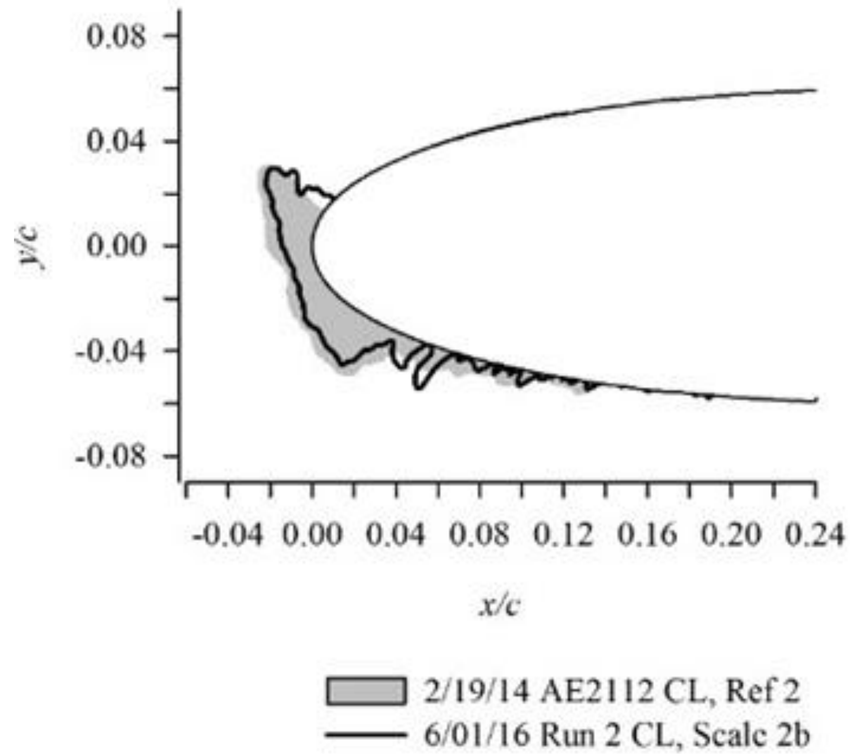
# Ice Shape Comparisons to Reference Shapes

## Reference Condition 2, V = 130 knots




$MVD_2 = 22\ \mu m$, $LWC_2 = 1.00\ g/m^3$, $t_2 = 6$ min
$MVD_{2a} = 20.8\ \mu m$, $LWC_{2a} = 2.15\ g/m^3$, $t_{2a} = 2.9$ min

## Bimodal Distribution (a)

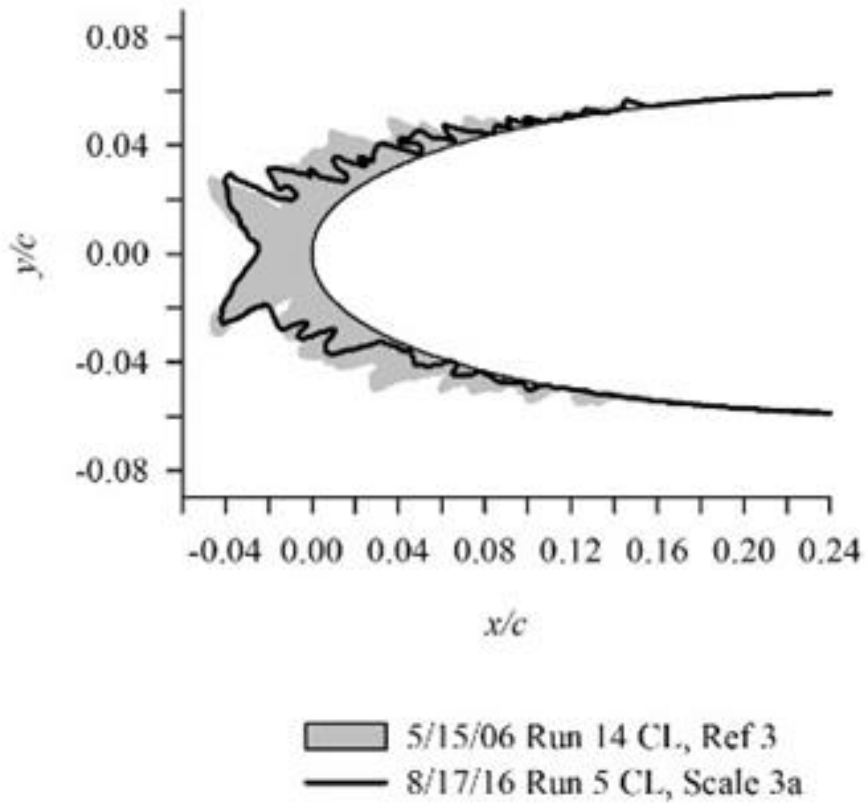



$MVD_2 = 22\ \mu m$, $LWC_2 = 1.00\ g/m^3$, $t_2 = 6$ min
$MVD_{2b} = 19.3\ \mu m$, $LWC_{2b} = 0.55\ g/m^3$, $t_{2b} = 11.5$ min

## Monomodal Distribution (b)

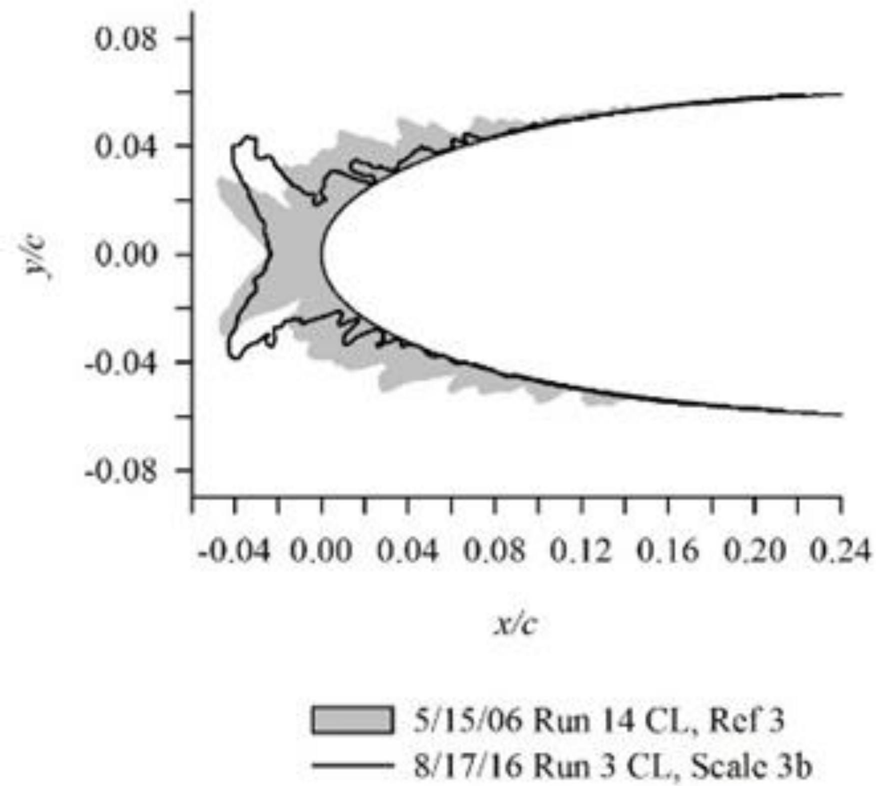
# Ice Shape Comparisons to Reference Shapes

## Reference Condition 3, V = 150 knots




$MVD_3$ = 30 μm, $LWC_3$ = 1.34 g/m$^3$, $t_3$ = 5.5 min
$MVD_{3a}$ = 20.8 μm, $LWC_{3a}$ = 1.96 g/m$^3$, $t_{3a}$ = 4.2 min

## Bimodal Distribution (a)

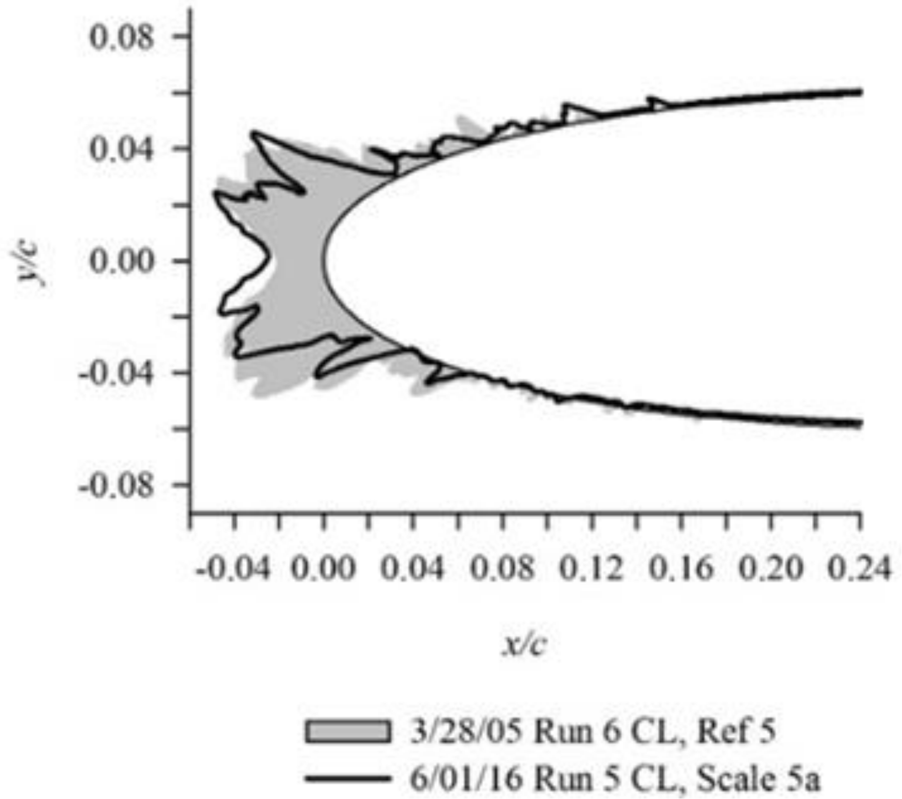


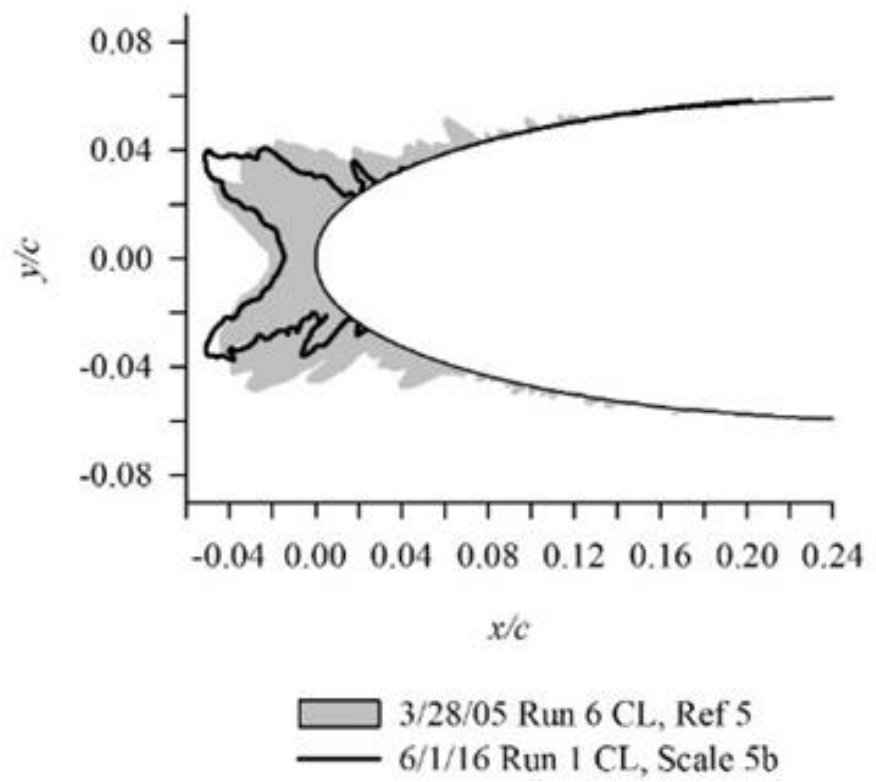

$MVD_3$ = 30 μm, $LWC_3$ = 1.34 g/m$^3$, $t_3$ = 5.5 min
$MVD_{3b}$ = 19.3 μm, $LWC_{3b}$ = 0.5 g/m$^3$, $t_{3b}$ = 17 min

## Monomodal Distribution (b)

# Ice Shape Comparisons to Reference Shapes

## Reference Condition 5, V = 250 knots



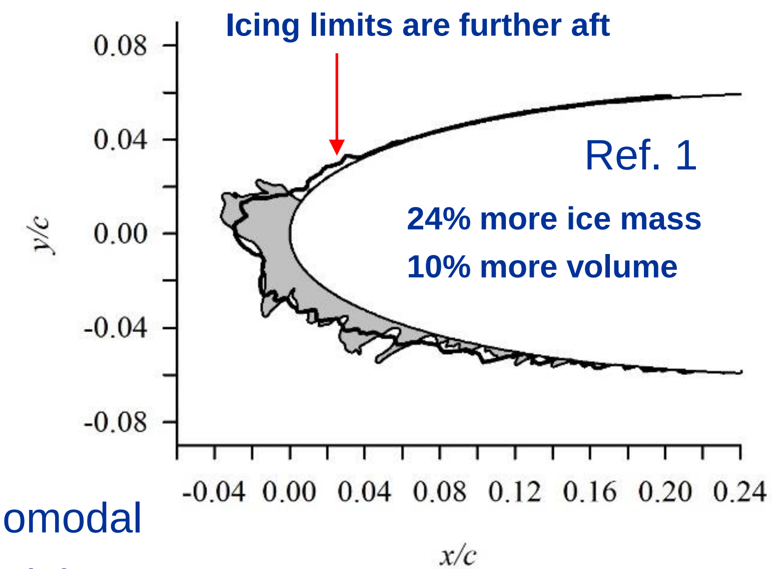

$MVD_5$ = 26.8 μm, $LWC_5$ = 0.56 g/m$^3$, $t_5$ = 8.5 min
$MVD_{5a}$ = 20.8 μm, $LWC_{5a}$ = 1.45 g/m$^3$, $t_{5a}$ = 3.5 min

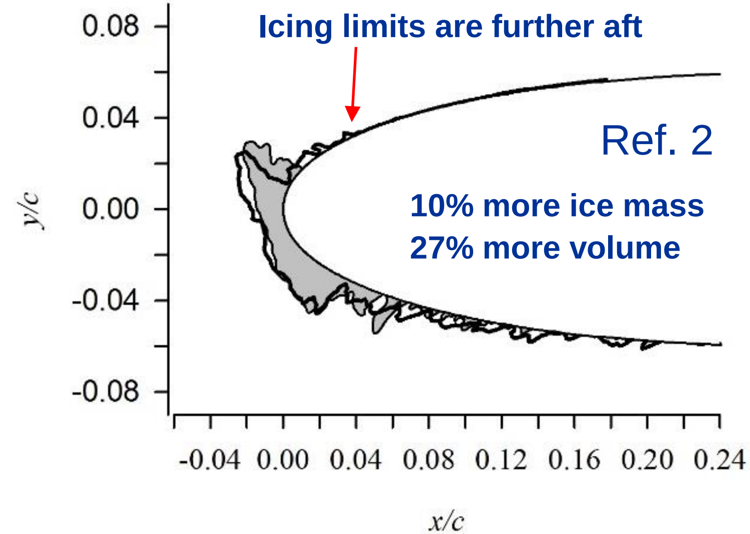
$MVD_5$ = 26.8 μm, $LWC_5$ = 0.56 g/m$^3$, $t_5$ = 8.5 min
$MVD_{5b}$ = 19.3 μm, $LWC_{5b}$ = 0.37 g/m$^3$, $t_{5b}$ = 14 min

## Bimodal Distribution (a)

## Monomodal Distribution (b)

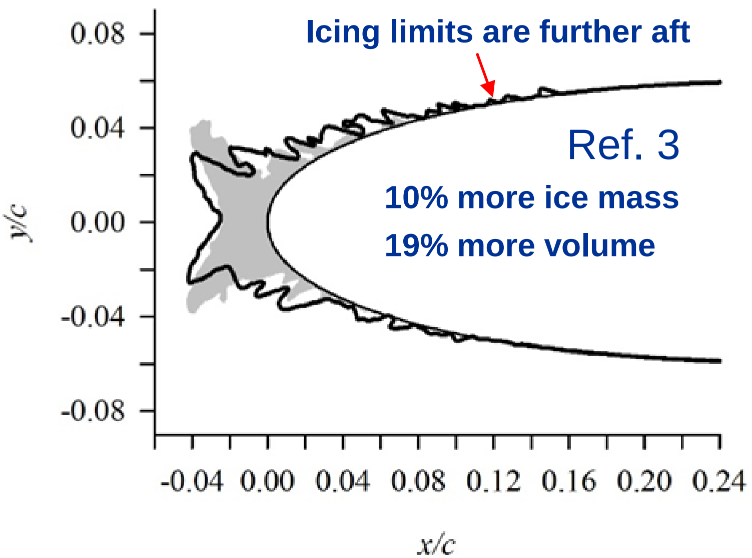
# Bimodal Cloud Effects on Ice Shapes

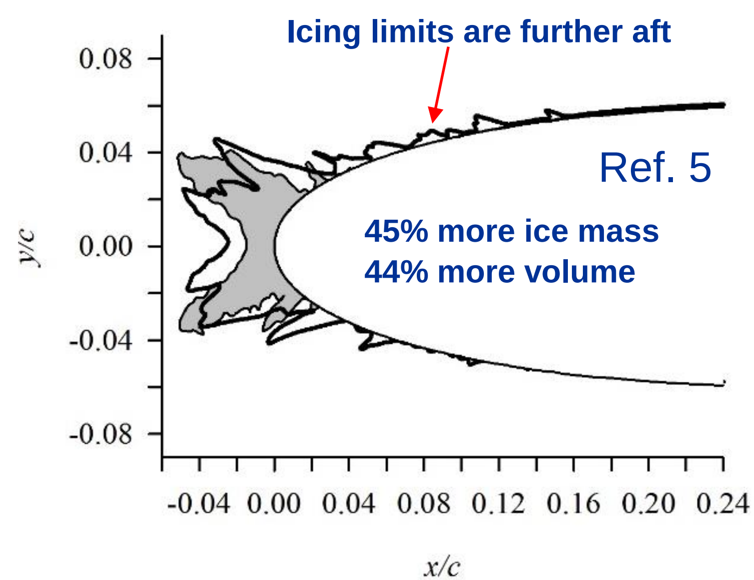



monomodal

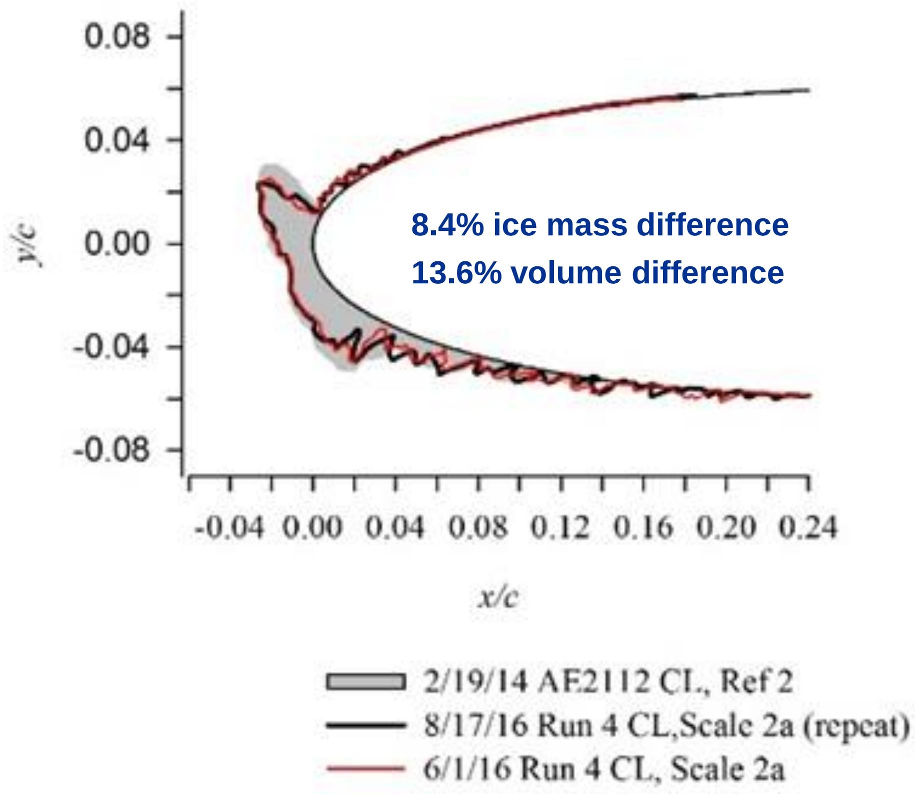
bimodal

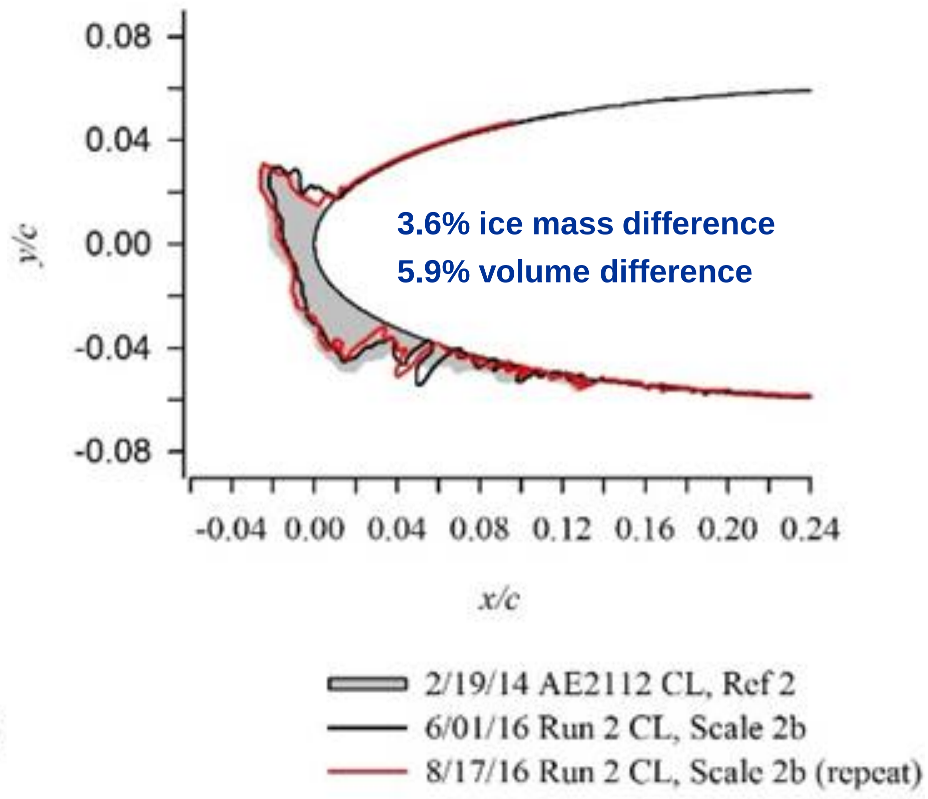


# Ice Shape Repeatability

## Reference Condition 2

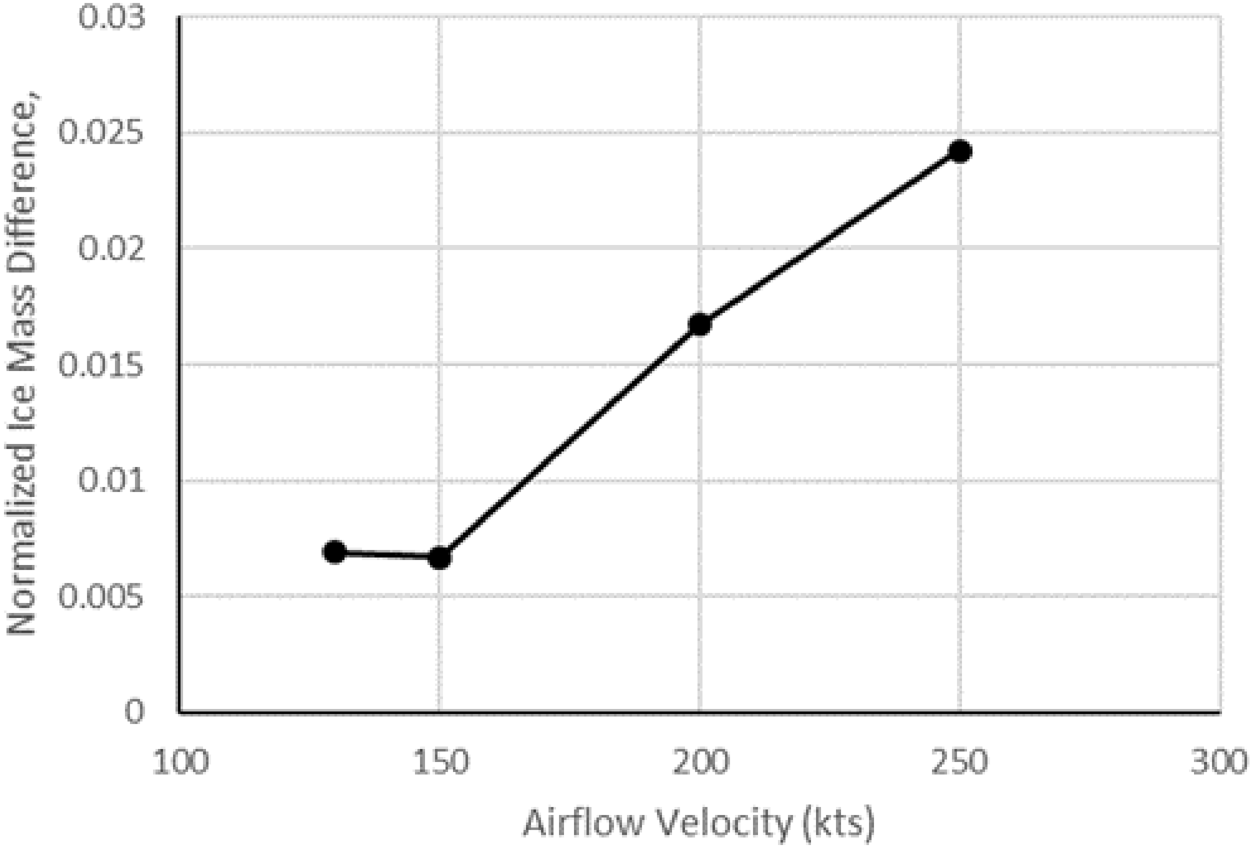



Bimodal Distribution (a)

Monomodal Distribution (b)

# Normalized Ice Mass Difference




$$M_w = LWC \cdot V \cdot t \cdot A_p$$

$$\Delta\widetilde{m}_i = \Delta m_i / \overline{M_w}$$

$A_p$ = projected area

$\Delta m_i$ = measured mass difference

# Concluding Remarks

- Bimodal spray ice shapes were created based upon the simultaneous spray process of Steen and Ide
- Test conditions, using monomodal and bimodal spray distributions, were developed for comparison to previously tested and recorded conditions
- For conditions that were the nominally the same, using the Olsen scaling method, the bimodal ice shapes:
  - ✓ Had a larger mass
  - ✓ Had a greater volume
  - ✓ Had icing limits further aft on the airfoil
- The ice mass difference seemed to increase with increasing velocity
- These differences seemed to be somewhat larger than repeatability
- More Evaluation Tests Recommended

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